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Multibeam Data Evaluation for DOLPHIN and Ship Collection Platforms

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This report presents an evaluation of the performance of the Deep Ocean Logging Platform with Hydrographic Instrumentation and Navigation (DOLPHIN) Remotely Operated Vehicle (ROV) as a platform for collection of multibeam sonar data to produce bathymetry. Three data sets were collected during the scheduled survey tests and are available for evaluation and comparison. The three surveys were conducted in the Norfolk Canyon off the mouth of Chesapeake Bay in Virginia. The DOLPHIN, equipped with an EM1000 echo sounder with EM100 electronics, and the National Oceanic and Atmospheric Administration's ship *Whiting*, carrying a Hydrochart II (HC II) sonar, surveyed from 5 to 7 August 1992, with the *Whiting* acting as the DOLPHIN's mother ship and following the DOLPHIN a few hundred meters behind. The USNS *Littlehales* conducted its survey of the same area from 23 to 25 August 1992, with a hull-mounted EM100 echo sounder.

The quality of the multibeam data collected by DOLPHIN is evaluated in terms of the root-mean-square (rms) noise in each beam, the frequency of dropouts suffered, and the presence of spurious noise, and is compared to data from the *Littlehales*/EM100 and the *Whiting*/HC II. The frequency, amplitude and distribution of heave, roll, and pitch of the DOLPHIN/EM100 are investigated, and when possible, compared to the corresponding data from the *Whiting*. Results indicate the DOLPHIN is a stable survey platform for multibeam data, which introduces negligible noise to the system and has very infrequent dropouts. Gridded bathymetry from the three platforms are compared and show good agreement. The least rms difference was found between the bathymetry produced by DOLPHIN and that generated with data collected by its mother ship. The largest rms difference was between the DOLPHIN and the *Littlehales*. Repeatability tests yield a consistent bathymetry for the DOLPHIN.

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Multibeam Data Evaluation for DOLPHIN and Ship Collection Platforms

1.0 Introduction

Ocean mapping has traditionally been performed by survey launches or ships with hull-mounted transducers. These vessels are subject to severe heave, roll, and pitch, which then introduce depth measurement errors. For offshore surveys a ship with its inherent high operational cost must be used in place of the small survey launch. By traveling a few meters beneath the surface of the ocean, a Remotely Operated Vehicle (ROV) is relatively immune to the action of the waves and should therefore provide higher accuracy data at a smaller cost. As part of the Canadian Ocean Mapping System (COMS) project, it has been shown that using the Deep Ocean Logging Platform with Hydrographic Instrumentation and Navigation (DOLPHIN) ROV with an EM100 system provides a cost-effective mapping platform for coastal and offshore areas [1]. Productivity may be further increased by using two DOLPHINs alongside a mother ship with its own echo sounder in a configuration such as the one shown in Fig. 1[1]. The vessel acts as the mother ship for both ROVs and uses the Global Positioning System (GPS) for positioning. Large areas can be surveyed in shorter periods of time. Furthermore, Preston stated in [3] that in rough seas DOLPHIN could operate while neither a small nor a large ship could.

Many Navy efforts have focused on developing efficient hydrographic data collection platforms, as well as increasing the number of miles surveyed per survey ship. As part of these efforts, the Naval Research Laboratory (NRL) and the National Oceanic and Atmospheric Administration (NOAA) conducted a joint test and evaluation of the DOLPHIN/EM100 system. The DOLPHIN tests were conducted over the period of 29 July 1992 through 8 August 1992 with a DOLPHIN owned by the Canadian Hydrographic Service (CHS) and operated by Geo-Resources, Inc. (GRI) of Newfoundland, Canada. The survey lines were run from 5 August 1992 through 7 August 1992. The DOLPHIN was remotely operated from NOAA's ship *Whiting* using a Ultra High Frequency (UHF) radio link.

[1] Reproduced from [2]

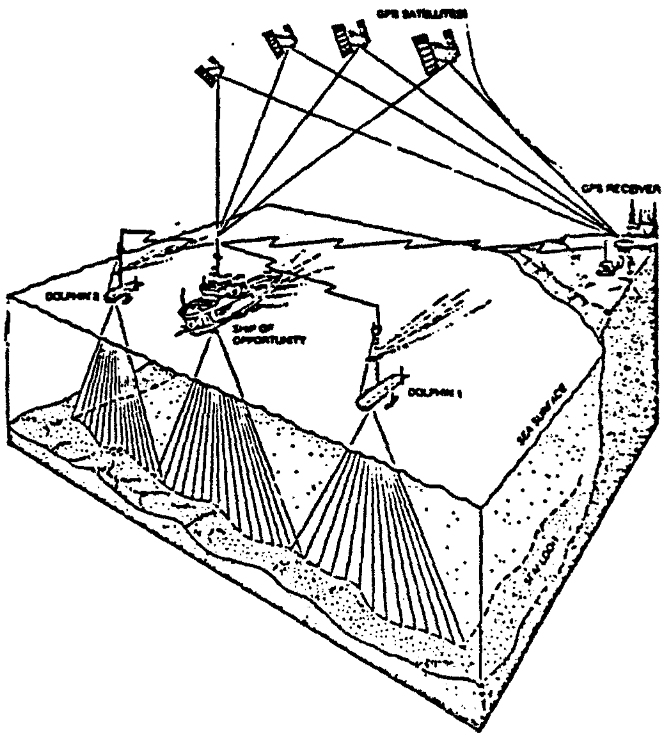

Fig. 1: Survey configuration with two DOLPHINs

The data collected consisted of along- and across-track lines in a preselected site over the Norfolk Canyon, as well as transit data with shallow and intermediate depth waters. Patch tests were also run for pitch, gyro, time delay, and roll. The surveys were conducted with the DOLPHIN several hundred meters directly ahead of NOAA's ship *Whiting*. The *Whiting*, equipped with a Hydrochart II (HC II) sonar, collected data over the same lines so that two data sets obtained with very similar conditions are available for comparison. Unfortunately, the DOLPHIN data were collected by a SIMRAD EM1000 transducer with EM100 electronics, a different multibeam sonar. The USNS *Littlehales* ran the same lines during the week of 23 August 1992, giving a third data set for evaluation. The *Littlehales* also collected data with an EM100 multibeam sonar.

Preston's evaluations [3] showed that DOLPHIN's pitch was smaller and at a lower frequency than that of the ships that ran the same survey, and

he concluded that DOLPHIN is more stable in pitch than a 500-ton ship. DOLPHIN's heave in quartering seas was considerable and similar to that of the ships. He also showed that when the ROV is towing a fish, it excites its towed downweight more than a ship, with quite a high frequency of the downweight depth. Some of the results presented in this report somewhat disagree with his conclusions.

This report is organized as follows. We first present brief descriptions of the DOLPHIN and the multibeam sonars used during the tests, followed in Section 3 by a description of the surveys and the tests performed. Section 4 presents the methods used to evaluate the DOLPHIN, while Section 5 presents the results. Attitude movement of the platform, frequency of dropouts, and beam and system noise were analyzed, and the bathymetry produced by the data collected by the three systems were compared. A companion report [4] presents details on DOLPHIN's performance, logistics, operation, and manpower requirements.

2.0 System Descriptions

Brief descriptions of the DOLPHIN and the sonar systems used for the tests conducted for DOLPHIN's evaluation are given in this section. The echo sounders are SIMRAD's EM100 and General Instrument Corporation's (GIC's) HC II.

2.1 The DOLPHIN

The DOLPHIN is a torpedo-shaped snorkeling semisubmersible ROV that weighs 3.3 tons and measures 7.6 m in length and approximately 1 m in diameter. It usually travels about 3 m below the surface of the sea. It can travel at speeds up to 14 kt up to 6 km away in Line Of Sight (LOS) from the mother ship. The DOLPHIN's 5 m mast is used for air intake to the diesel engine and for the UHF radio and GPS navigation antennae. Details about DOLPHIN's design and operation are given in [1] and [4].

2.2 The SIMRAD EM100

The EM100 is a multibeam echo sounder that operates at 95 kHz, with a maximum of 32 receiving beams and 3 possible athwartship beam apertures.

Table 1: Beamforming modes of the EM100

Mode	Swath width degrees	No. beams	Beam width degrees	Coverage times water depth
Ultrawide	100	27	3.75	2.4
Wide	80	32	2.50	1.7
Narrow	40	32	2.00	0.7

The alongship beam aperture is fixed at 3^0. The beamforming modes of the EM100 are shown in Table 1. The maximum coverage is 100^0, corresponding to 2.4 times the water depth using the ultrawide mode. The beam fan is electronically stabilized in roll and mechanically in pitch. The transducer may also be mounted without pitch stabilization. For transmission each transducer element is connected to separate power amplifiers. The transducer array consists of 96 individual elements 80 cm wide and a curvature of 45 cm. The elements have common transmission/reception functions. Designed to be mounted on a retractable hull unit, the EM100 was specifically developed for continental shelf and coastal water survey tasks. The hull unit allows the transducer to be lowered to a position approximately 1 m below the hull during a survey to avoid air bubbles. The DOLPHIN does not have the retractable hull unit.

The EM100 has an operating range between 10 and 600 m of depth. SIMRAD claims accuracies better than 0.5% of the water depth across the entire swath [5]. The collected data are stored in digital form in depth, position, and miscellaneous datagrams. It can acquire up to about 3 Mbyte of bathymetric data per hour and more in shallow water [2]. A heave/roll/pitch sensor with good accuracy must be connected to the multibeam echo sounder. Depth data will then be corrected for ship motion. Tide compensation is performed in the postprocessing phase.

2.3 The Hydrochart II

GIS's HC II is a dual transducer multibeam sonar system that operates at 36 kHz. The system uses a cross-fan transducer array to produce 9 beams for

port and 9 for starboard, with overlapping near-nadir beams. The system switches between the two sets of nine beams each ping cycle. The swath coverage of the HC II is 2.5 times the water depth or 105^0.

A Differential Global Positioning System (DGPS) was used as the primary navigation system for the survey. Two differential receivers were used to monitor the differential correctors and compute geographic positions.

3.0 Area Surveyed

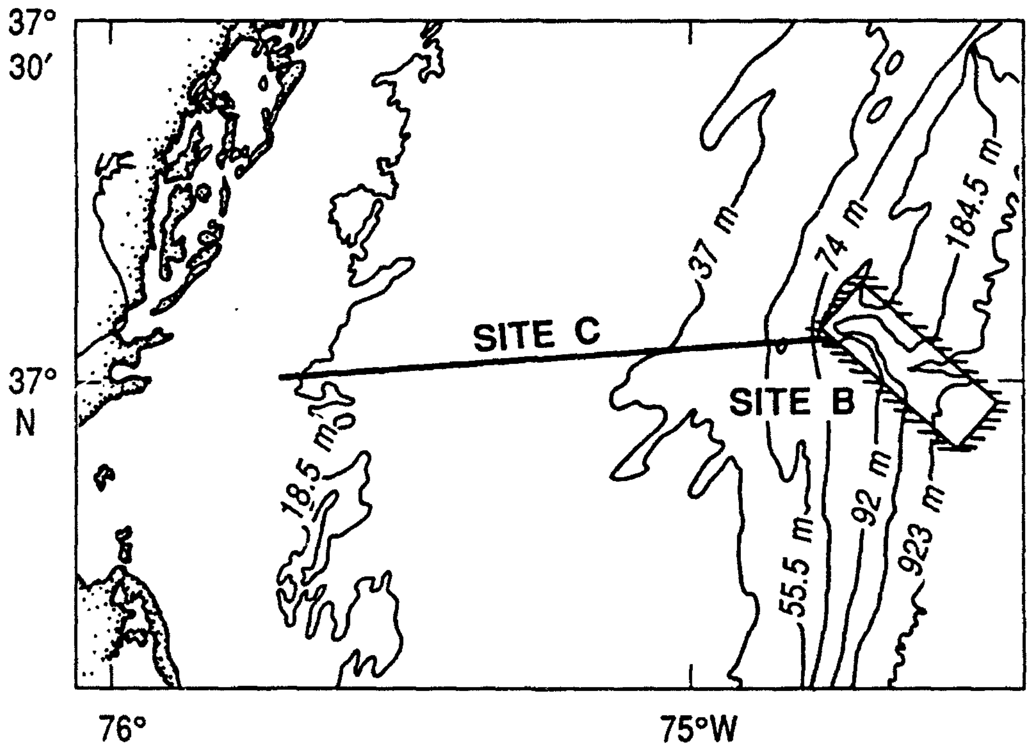

Fig. 2: DOLPHIN evaluation test areas

The area surveyed consisted of the preselected Site B in the Norfolk Canyon and transit data from and to the station. The center of Site B was located 62 nmi east of Cape Charles, Virginia, at Norfolk Canyon. The surveyed areas are shown in Fig. 2. The survey lines, run by DOLPHIN in Site B, are shown in Fig. 3, where lines B03 through B08 are the lines parallel to

the contours and shown left to right, and lines B21, B22, the pitch test lines, and B24 are perpendicular to these, and shown from top to bottom of the figure. Site B was approximately 2400 m (1.3 nmi) by 5500 m (3 nmi).

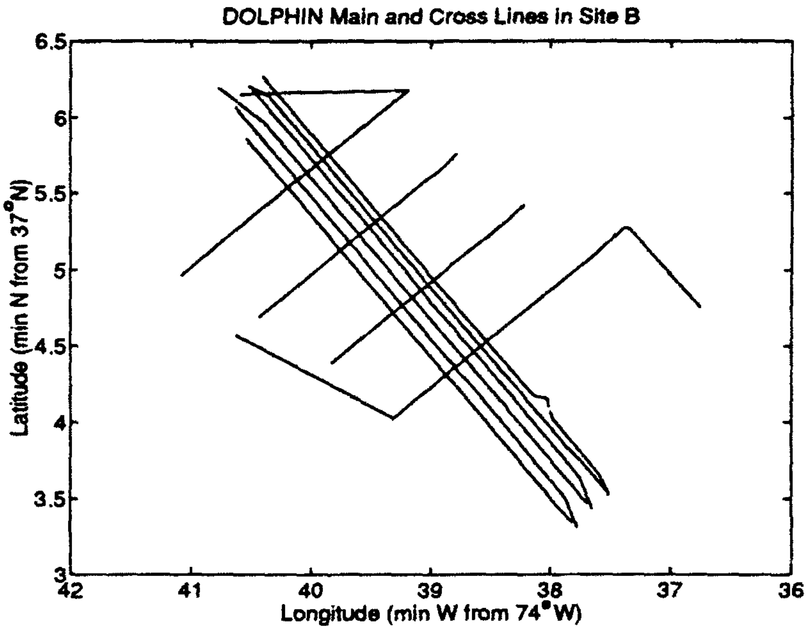

Fig. 3: Survey lines of Site B

The project consisted of several tests designed to provide data for the evaluation of DOLPHIN's performance. The tests were as follows:

Patch Test: *Whiting* held station while DOLPHIN conducted a patch test. The patch test consisted of six lines, two perpendicular to the contours to evaluate pitch errors, and two sets of reciprocal lines perpendicular to each other to evaluate roll errors.

Accuracy Test: It consisted of six main lines (B03–B08) run parallel to the contours in Norfolk Canyon. Line spacing was selected to overlap for comparison of EM100 outer beams of one line with the inner beams of the next line. Three up-down slope crosslines (B21, B22, B24) were run perpendicular to the main-scheme lines.

Sea State Test: Line B05, run during the accuracy test with calm seas, was repeated with a rougher sea state of light chop and 3-ft swells (line B05a). The intent of this test was to evaluate the effects of sea state on the acquired data.

Feature Presentation: Survey lines were planned to run perpendicular to the contours of a very steep feature in the Norfolk Canyon. The intent was to see if there was any time lag in the data logging by comparing contours acquired running upslope with those acquired running downslope. When the lines were run, the depicted feature was not found.

Heave Test: Two sets of reciprocal lines (HT1a, HT1b, HT2a, HT2b) were run perpendicular to each other in a shallow flat area. The intent was to get data that could be used to evaluate heave effects on the platform.

Transit Data: *Whiting* and DOLPHIN collected simultaneous data while transiting to and from the survey area. This long line provides additional data for comparisons.

Sea conditions on the first day of the survey (5 August 1992) were calm, with no wind waves and no swell. On the following two days there was a light chop with 3-ft swells.

4.0 Tests and Evaluation Methods

This section describes the different tests and processing applied to the collected data sets. The purpose is to evaluate the performance of the DOLPHIN ROV as compared to ship-collection platforms, and in particular, the resulting bathymetry.

To fairly compare one system to another, all environmental variables such as ship's speed and sea state should be the same for all tests and constant for the duration of the test. When this was not possible (such as comparison to *Littlehales* data collected on a different date), we tried to minimize the effects or make comparisons that are robust with respect to changes in these conditions. For example, when computing the system dependent noise analysis we compared data from the *Littlehales* to data from the DOLPHIN, while comparison of pitch data (which is sea state and platform dependent) was performed between the *Whiting* and the DOLPHIN. Bathymetry comparisons were performed between the three possible pairs of platforms.

4.1 Attitude Movement Tests

The contributions to depth error come from the lack of knowledge of ray bending, roll angle, pitch angle, and heave. All of the above plus yaw produce position errors. Both depth and position are degraded with roll errors, but only position is affected appreciably for the inner beams, and only position is significantly affected by pitch [6]. The contribution of yaw to the error in depth is negligible except when the slope of the bottom is steep. An error in heave contributes to errors both in depth and beam position. Since heave, roll, and pitch all affect either positioning or depth calculations, or both, it is important to determine DOLPHIN's movement during a survey and how it compares to the ship platform.

We analyzed the amplitude of heave, roll, and pitch vs. time, as well as their power spectra which yield information about their frequency response. The beam data of the echo sounders is not sampled uniformly, so interpolation to obtain evenly spaced amplitude vs. time is performed prior to computing the power spectra with fast Fourier transform (FFT) routines. Low-pass interpolation is performed using a symmetric filter that allows the original data to pass through unchanged and interpolates between data points. Statistics of the attitude data, such as mean and variance, are

computed and their distribution is also estimated. Unfortunately the data files from *Whiting*/HC II that we were able to read (merged .SBO files) do not contain the needed attitude data; these merged files only contain pitch information.

4.2 Dropouts

We define dropout as depth samples that are set to zero by the system as a result of an error check or due to the impossibility of obtaining a depth measurement for the corresponding sample time. The number of dropouts gives an idea of the robustness of the combination of system and platform. We compare the number of dropouts of the DOLPHIN data to the number of dropouts of data from the *Littlehales*, the two platforms carrying the EM100 echo sounder.

4.3 Beam and System Noise

In order to investigate how noisy the different systems are, and how noisy the various beams of each system are, we performed fits to the depth vs. time data for each beam, subtracted the fitted data from the collected data, and assumed the residue to be noise. The procedure is shown graphically in Fig. 4, where DOLPHIN data from the center beam of line B03 were used. All dropouts are discarded before data fitting and computation of noise since they will significantly affect the outcome.

The following filtering technique is used to obtain a smooth fit to the raw data: Decimation is first implemented by low-pass filtering the raw de-meaned data with an eighth order Chebyshev filter and then resampling at a lower rate. Low-pass interpolation is then applied to the resampled data to obtain the smooth curve that fits the original data. This interpolation is implemented by passing the decimated data through a symmetric digital filter that minimizes mean square error. The mean is then added back in after interpolation. A spline fitting method yields almost identical results.

In order to obtain valid conclusions when comparing noise in the different beams of a single system, the analysis is done using data from flat areas, such that all beams are steered to regions of similar depths. Noise levels are not only dependent on the beam number and system but also on the operating depth; this is clear in Fig. 4 where we see the noise level increasing

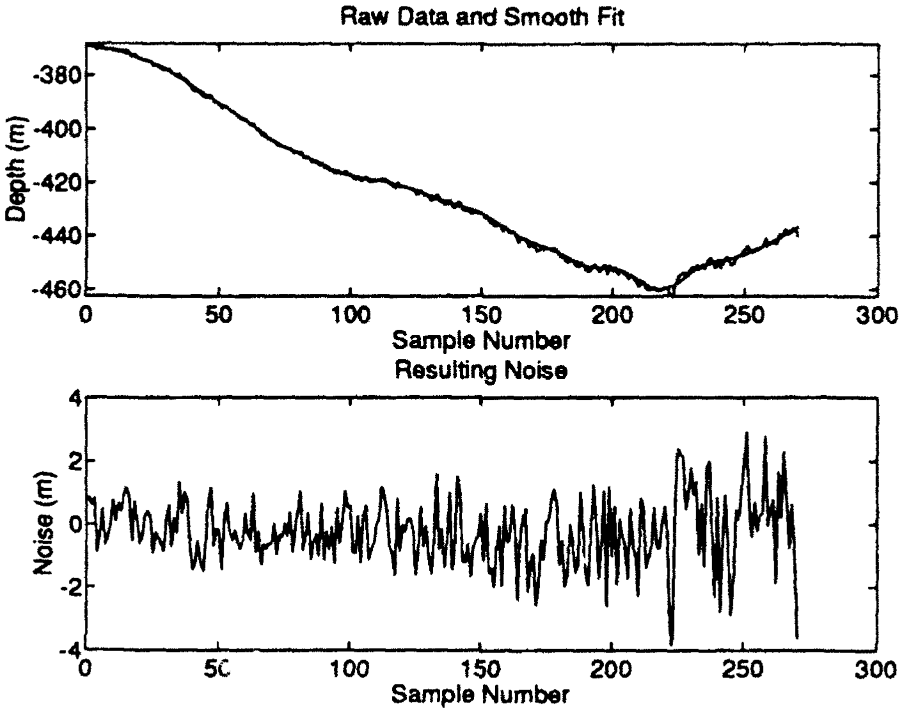

Fig. 4: Noise analysis procedure

with increasing depth. On the other hand, when we compare noise between systems, we use larger sets of data that include different morphology.

In [7] the author gives precision in terms Root Mean Squared White Noise (RMSWN). The method described there yields the system's noise provided that the spectrum flattens out in the last 10%, and this 10% represents the system's noise. The spectra of the depth signals we analyzed in this report do not flatten out nicely so this method was not used.

4.4 Comparison of Bathymetry

Bathymetry is produced by postprocessing the multibeam data collected during a survey, although near-real-time bathymetry is certainly possible. The bathymetry is a triplet (Lat,Lon,Depth) that describes the topography of

the surveyed area. Both the EM100 on the DOLPHIN and the HC II on the *Whiting* recorded position as latitude and longitude, while the EM100 on the *Littlehales* used UTM coordinates. All three systems recorded depth in meters. After merging depth with position, the HC II "merged files" contain depth quantized to 1 m; the EM100 depth datagrams register depth quantized to 0.075 m.

Even if the systems were perfect and independent of environmental variables such as weather and sea state, and the processing algorithms were the same for all systems, we would not expect the triplets to be identical regardless of the systems used to collect the data. Not only is the original point bathymetry different, but also further differences are introduced with the gridding routines used [8]. Here we compare bathymetry produced by the three platforms, as well as bathymetry collected by the same platform — the DOLPHIN — on different dates.

Standard bathymetry processing yields data that are unevenly spaced. Before comparing bathymetry we grid the position to a common evenly spaced lat/lon grid. The grid is often determined by the average distance between closest neighbors in the unevenly spaced data with the coarsest grid. Other times the gridded interval is determined by other factors, such as scale of the desired map or processing time required. Once the data sets are all in a common grid, the difference between them, ΔZ, is analyzed by computing the mean difference between platforms, μ, the sample standard deviation of the difference, σ, and the rms difference, where these quantities are defined in the usual way, and given in (1)-(4), respectively, for continuity. Notice that σ and rms are identical if the data have zero mean or if they are demeaned for processing, and they are therefore frequently used interchangeably.

$$\Delta Z_i = Z_{a_i} - Z_{b_i} \tag{1}$$

$$\mu = \frac{\sum_{i=1}^{N} \Delta Z_i}{N} \tag{2}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (\Delta Z_i - \mu)^2}{N-1}} \tag{3}$$

$$rms = \sqrt{\frac{\sum_{i=1}^{N} \Delta Z_i^2}{N-1}} \tag{4}$$

It must be noted that the comparisons and the statistics and conclusions obtained from them are dependent on the gridding (interpolation and extrapolation) routines used [8]. We tried to avoid extrapolations by only comparing areas common to all data sets used; this unfortunately, means that we have to work with numerous very small areas instead of a single larger area.

The standards of the International Hydrographic Organization (IHO) [9] for depth soundings require that with a probability of at least 90%, the total error should not exceed 0.3 m at depths between 0 and 30 m, and 1% of the depth for depths greater than 30 m.

4.5 Repeatability Test

The repeatability analysis is also a comparison of bathymetry, but between results generated from data sets collected by the same platform — in this case, the DOLPHIN — at different times, and with similar conditions. These results are not expected to match perfectly but are expected to closely agree. The procedure used is the same as that described in the previous section. When data for a given line are collected with different sea states, comparing bathymetry produced by the two surveys could give an indication on how these conditions affect the platform.

5.0 Results

Results of the data analysis performed to evaluate the DOLPHIN as a multibeam sonar data collection platform using the methods just discussed are given in this section. We begin by presenting some results about the attitude data.

5.1 Analysis of Attitude Test Data

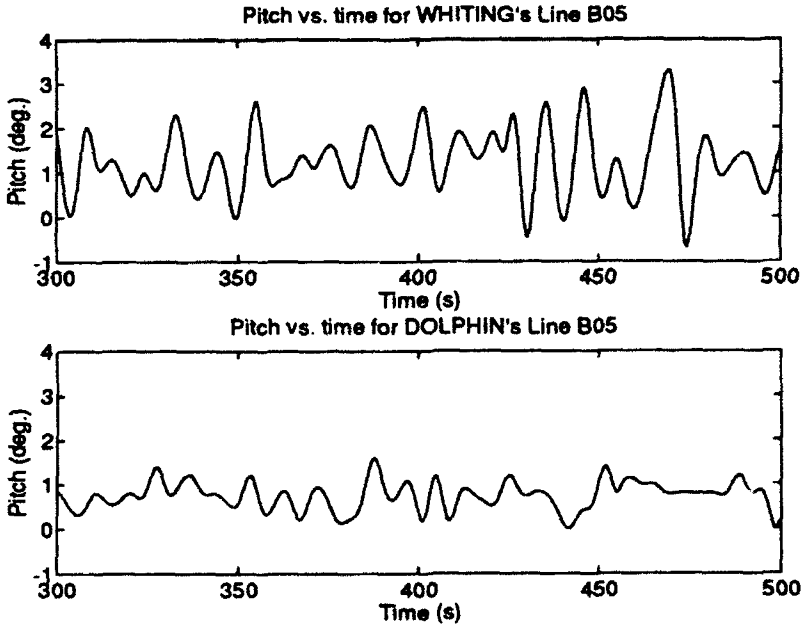

Fig. 5: Pitch vs. time (line B05)

We analyzed pitch data from the *Whiting*/HC II and pitch, heave, and roll data from the DOLPHIN/EM100. Pitch, heave, and roll are also available for the *Littlehales*, but since this ship surveyed the area on a different date, comparisons to the DOLPHIN were not made.

Figure 5 shows filtered pitch vs. time for both the *Whiting* and the DOLPHIN for line B05, one of the main lines in Site B. The plot shows smoothed (low-pass filtered) data to try to eliminate the visual quantization effects that

are different for the two systems and, more importantly, to minimize differences due to the much lower sampling rate of the HC II. The actual pitch recorded by the HC II is quantized to 0.1^0, while the EM100 quantizes pitch[2] to 0.2^0. Figure 5 shows that DOLPHIN's pitch for line B05 is considerably smaller than that of the *Whiting*; analysis of a large set of data indicates this is not typically the case, which disagrees with Preston's conclusions [3]. We suggest that the direction of the ship's motion and the way in which the waves hit the vessels (e.g., quartering vs. head seas) have a large influence on the platform's pitch.

Table 2: Pitch data

Platform	Line	course	max |pitch|	mean	σ	max variation
DOLPHIN	B03	139^0	1.8	0.8	0.25	1.3
Whiting			3.1	1.1	0.65	2.1
DOLPHIN	B04	319^0	2.8	0.7	0.70	2.1
Whiting			2.6	1.2	0.49	1.4
DOLPHIN	B05	139^0	1.8	0.7	0.31	1.9
Whiting			3.6	1.2	0.72	2.6
DOLPHIN	B06	319^0	2.6	0.6	0.66	2.2
Whiting			2.3	1.1	0.47	1.6
DOLPHIN	B07	139^0	1.8	0.8	0.31	1.2
Whiting			3.0	1.2	0.80	2.1
DOLPHIN	B08	319^0	3.6	1.0	0.72	2.6
Whiting			2.4	1.2	0.43	1.2
DOLPHIN	B21	231^0	2.8	0.7	0.83	2.1
Whiting			2.6	1.0	0.56	1.6
DOLPHIN	B24	051^0	1.8	0.6	0.28	1.2
Whiting			2.6	1.0	0.67	1.7

Table 2 shows some statistics for the pitch data from DOLPHIN and *Whiting* for several lines in Site B. Clearly, we cannot conclude that the

[2] Documentation [5] states that pitch is quantized to 0.1^0.

ROV pitches less than the ship. The results for this particular survey of Site B consistently indicate that the DOLPHIN pitched less with one direction seas, but has a larger pitch amplitude with opposite seas. Also notice that when the pitch amplitude of the DOLPHIN is larger it is so by a small amount most of the time, while the difference is much larger when its pitch is smaller that the *Whiting*'s. The standard deviations of the pitch of both platforms are very dependent on the direction of travel and so is the maximum variation. Also clear in Table 2 is that both platforms had a pitch bias, the DOLPHIN's bias being smaller, about 0.6^0 bow down[3]. DOLPHIN is pitched down slightly on purpose to avoid surfacing.

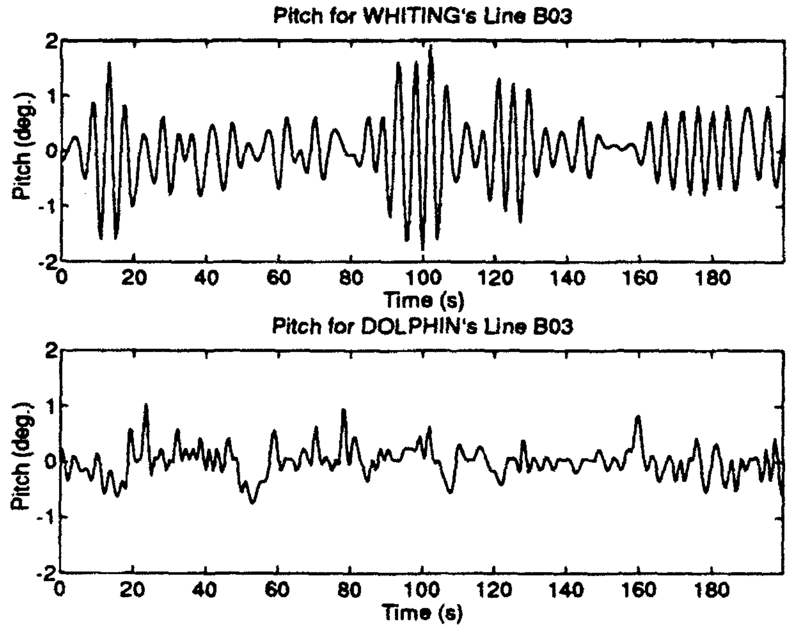

Fig. 6: Pitch vs. time (line B03)

In Fig. 6 we plotted the variation in pitch about the mean for a section of line B03 for both *Whiting* and DOLPHIN. In both cases the data were interpolated to a common sampling rate, and therefore, smoothed. Notice

[3]Patch tests were conducted to determine biases. Although patch test data have not yet been analyzed, we expect results to agree with those given here.

that the ship's pitch for line B03 has spurts of large amplitude. We found these spurts to be characteristic of most of the pitch data from the *Whiting*, and also from the *Littlehales*, although this behavior is not constantly present. For example, the spurts on line B05 cease after about 250 s and are therefore not seen in Fig. 5. Nothing like it appears on the pitch data from the DOLPHIN. Figure 7 shows this behavior for the *Littlehales*.

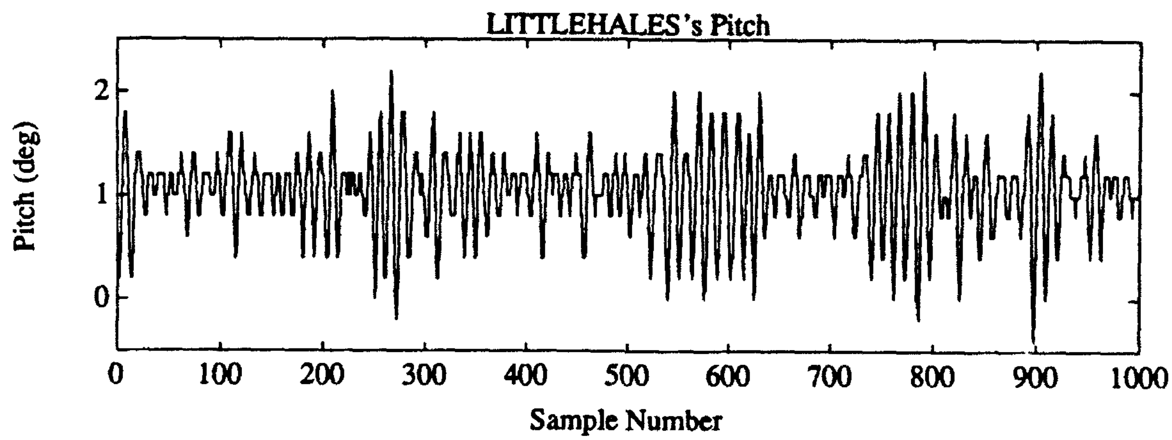

Fig. 7: Pitch vs. sample number for *Littlehales*

Figure 8 shows the power spectrum of pitch for both the DOLPHIN and the *Whiting* for line B03. In this figure the frequency axis is given as normalized frequency where 1.0 corresponds to half the sampling rate, or 0.5 Hz at the sampling frequency of $f_s = 1.0$ Hz. We see that DOLPHIN's spectrum is quite flat for all frequencies (i.e., white), while *Whiting*'s decays more rapidly. This confirms what we see in Fig. 5 and especially in Fig. 6, that is the random-like behavior of the pitch of the DOLPHIN. Also, DOLPHIN's pitch peaks at a lower frequency than *Whiting*'s, which agrees with results presented in [3].

Figure 9 shows some results of the analysis of heave data from DOLPHIN for a section of line C. The top plot shows the depths of the center of the EM100; the middle plot shows the heave registered, and the bottom figure shows the noise present in the center beam. It was thought that noise was mainly due to heave effects, and we therefore investigated the correlation between the two. We found no evidence that the noise is highly correlated

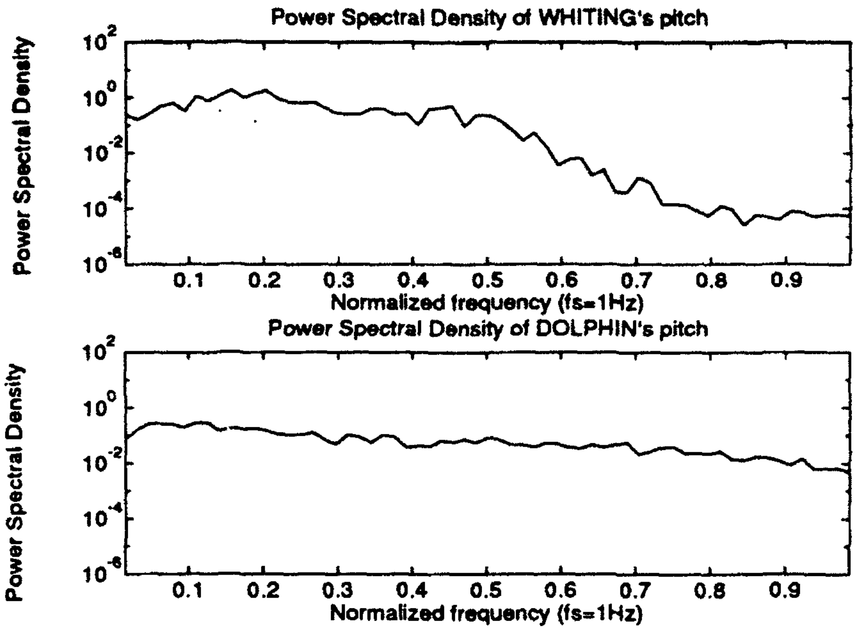

Fig. 8: Power spectral density of pitch (line B03)

to the heave, although we see that the amplitude of the heave is very similar to that of the noise. Analysis of DOLPHIN data from the heave test area indicates the power spectrum of DOLPHIN's roll peaks around 0.085 Hz, or a period of approximately 12 s. The distribution of the roll is very close to normal, with a roll bias of about 1.25^0 to starboard. The pitch bias of the DOLPHIN in this area is about 0.7^0 and doesn't change much with time and change in course. The major frequency component of pitch for this area is around 0.089 Hz, although another very strong component appears at a little less than half this frequency. The rms value of DOLPHIN's heave, pitch, and roll in this area are approximately 0.2 m, 0.3^0, and 0.9^0, respectively.

DOLPHIN's transit data, i.e., line C, indicates that the frequency of roll is higher than that of pitch with the largest component with a period of about 7 s. The spectrum of roll does not change much until about 0.3 Hz. The rms roll is about 0.6^0, while the rms pitch is about 0.3^0. The probability density function (pdf) of roll looks Gaussian, but the distribution of pitch seems more like a Laplacian pdf. The histograms of heave data for line C

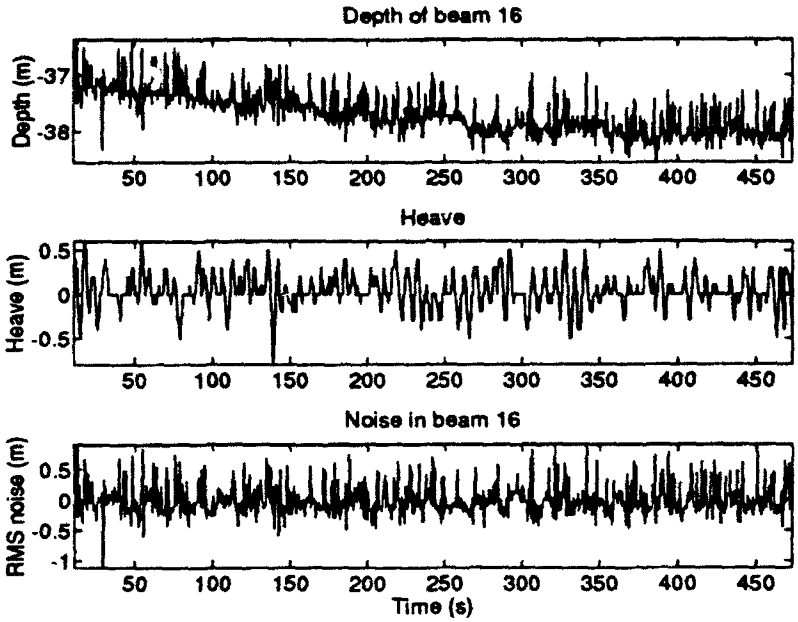

Fig. 9: Depth, heave, and noise

also show a Laplacian-like pdf for DOLPHIN's heave, with a mode of zero and quite symmetric around its mean. The heave signal has a very strong sinusoidal component. Heave and roll are not available from the HC II merge files from the *Whiting*.

5.2 Dropouts

The number of dropouts for the *Littlehales*/EM100 was extremely large for all the data sets studied, while the corresponding number of dropouts for the DOLPHIN/EM100 was quite low, even for the outer beams. Table 3 lists the number of dropouts for the two platforms for a few of the survey lines. In this Table id means intermediate depth (around 500 m) and sh means shallow (around 50 m). There are 32 beams for the EM100, we chose to analyze only the center beam, beam 16, and an off-nadir beam, beam number 5. Notice the DOLPHIN suffered very few dropouts, even when sampling at rates comparable to the *Littlehales*'s; it is reasonable to expect

more dropouts at a higher sampling rate, that is why the average dropout rate (ADR) is listed in Table 3. The center beams of the ship usually suffered from considerably less dropouts than the off-nadir beams, while this was always the case for the ROV. It is not clear why the *Littlehales*'s center beam had more dropouts than its beam number 5 on line B03. This didn't happen to the DOLPHIN, and the depths are such that frequent dropouts are not expected.

Table 3: Comparison of dropouts

Platform	Line†	Beam No.	No. of Samples	No. of Drops	Sample Rate (Hz)	Drops % total	ADR‡ (Hz)
DOLPHIN	B06	16	1157	8	1.01	0.7	0.07
Littlehales			1665	251	0.99	15.1	0.15
DOLPHIN	B06	5	1157	10	1.01	2.6	0.03
Littlehales			1665	252	0.99	15.1	0.15
DOLPHIN	B21-22	16	1367	0	1.13	0.0	0.00
Littlehales			1351	94	1.21	7.0	0.08
DOLPHIN	B21-22	5	1367	33	1.13	2.4	0.03
Littlehales			1351	164	1.21	12.1	0.15
DOLPHIN	C	16	1000	0	1.18	0.0	0.00
Littlehales	(steep)		1000	124	0.97	12.4	0.12
DOLPHIN	C	5	1000	52	1.18	5.2	0.06
Littlehales	(steep)		1000	383	0.97	38.3	0.37
DOLPHIN	C (sh)	16	5994	3	1.99	0.1	1E-3
Littlehales	(flat)		6000	0	2.06	0.00	0.00
DOLPHIN	C (sh)	5	5994	3	1.99	0.1	1E-3
Littlehales	(flat)		6000	0	2.06	0.0	0.00
DOLPHIN	B03 (id)	16	890	25	0.49	2.8	0.01
Littlehales	(flat)		1440	422	0.77	29.3	0.23
DOLPHIN	B03 (id)	5	890	28	0.49	3.2	0.02
Littlehales	(flat)		1440	293	0.77	20.4	0.16

† sh: shallow; id: intermediate depth. ‡ Average Dropout Rate

The number of dropouts, both absolute and as percentage of total samples, and the ADR were much better for the DOLPHIN than for the ship, so there is more useful data for it than for the ship. This is important since not only can the DOLPHIN operate in adverse weather conditions when surface vessels cannot [3], but also a larger percentage of the data gathered by its EM100 in the same conditions is good.

Figure 10 shows the center beam depths vs. time recorded for the cross line B22 of the *Littlehales* and the DOLPHIN. Remember that conditions such as sampling rate, ship speed, and sampling duration are not identical, and therefore, at a given sampling time the two systems will be sampling two different points on the bottom; this explains the slight differences in the profiles shown. Since we were interested in studying and showing dropouts in the raw data, the depths shown in Fig. 10 were neither georeferenced nor corrected.

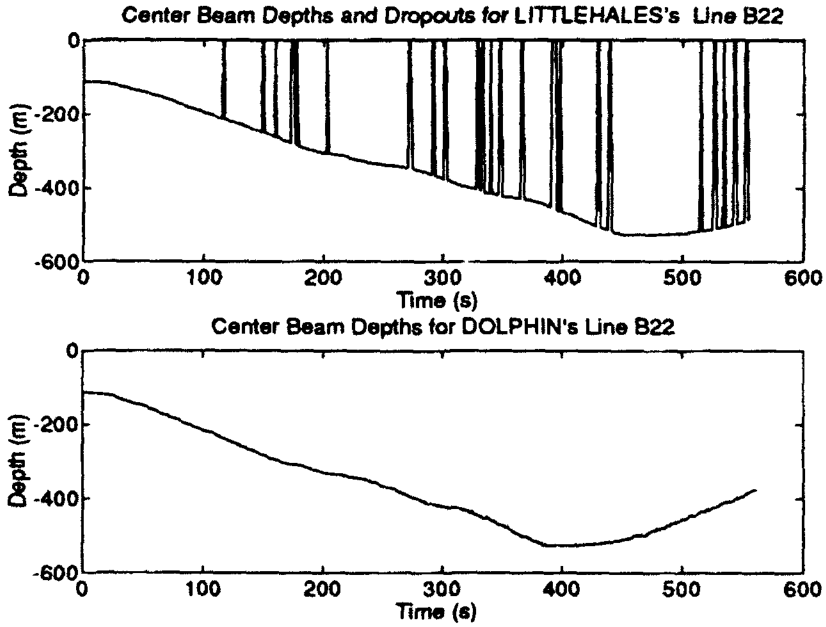

Fig. 10: Center beam data of line B22

Figure 11 shows plots of DOLPHIN and *Littlehales* data before and after removal of dropouts for a different line. These points could have been inter-

polated, but instead we simply discard the bad samples. *Littlehales* clearly has consistently more dropouts than does DOLPHIN, but also its sampling rate is higher, as shown by the x-axis (sample number) in the plots of Fig. 11. After discarding dropouts we see that the equivalent sampling rates of both systems become closer.

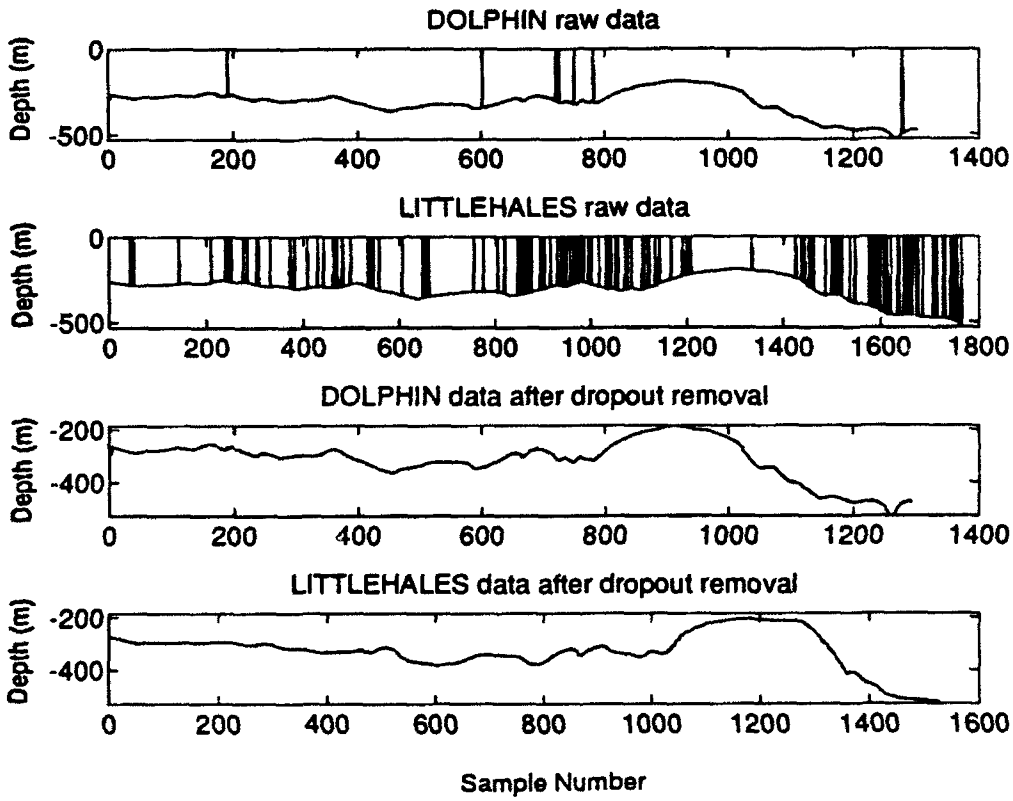

Fig. 11: Effect of dropout elimination

We also analyzed the number of dropouts as a function of beam number for both the *Littlehales* and the DOLPHIN for a section of line C. The results are shown in Fig. 12 for the bathymetry shown in Fig. 13. Almost all the dropouts the *Littlehales* suffered were going up the steep slope shown in Fig. 13. DOLPHIN seems to handle slopes much better. Notice that the dropouts are a much higher percentage of the total samples for the *Littlehales* than for the DOLPHIN, and also that for unknown reasons the center beams of

the *Littlehales* seem to dropout more frequently than those a little off-center; this behavior is not present on the DOLPHIN data, where the close-to-nadir beams suffer less dropouts than all others. Although the plot of dropouts vs. beam number is generally "U" shaped, we can see that it is not symmetric, with the DOLPHIN having more dropouts on its port side. It is not clear why the *Littlehales* didn't record any depths for beams 1 through 3, 31 and 32. It would seem that the ultrawide mode was used for all depths in the range shown in Fig. 13, which is not expected (see Table 1).

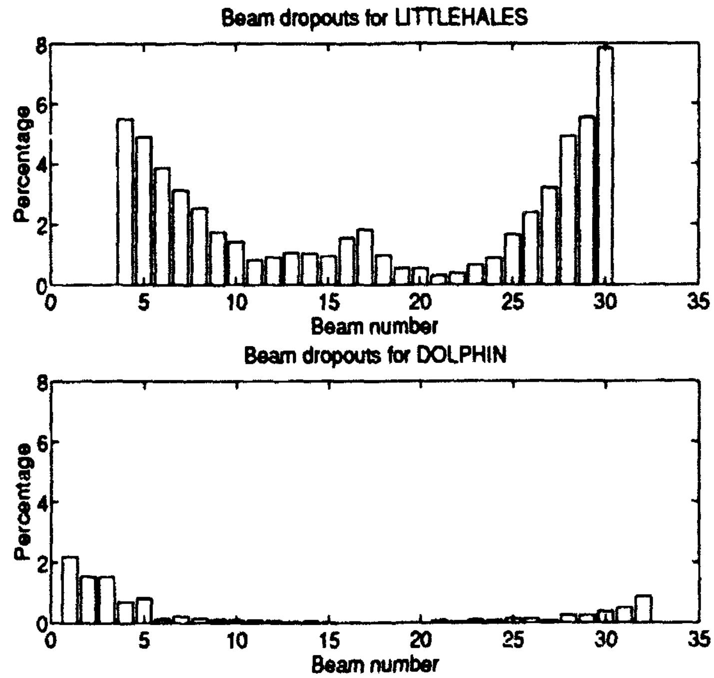

Fig. 12: Dropouts vs. beam number

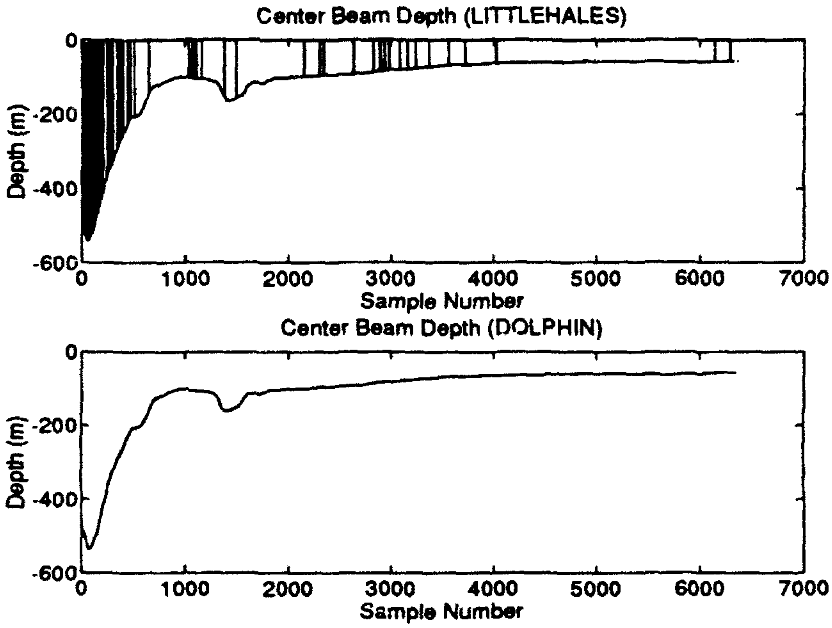

Fig. 13: Raw bathymetry of parts of line C

5.3 Beam Noise

Table 4 shows the standard deviation of the noise in the center beam (beam 16) of the EM100 on the DOLPHIN and the *Littlehales*, and in the two center beams (beams 9 and 10) of the HC II on the *Whiting* for three main lines and one cross line in Site B. The average depth of the line is given simply as a reference, since the area has steep slopes. Table 5 lists the same information for the two outermost beams (beams 1 and 10) of the EM100 for both the *Littlehales* and the DOLPHIN. Notice these tables are for intermediate depths waters. *Whiting*'s outermost beams were not tabulated in Table 5 because it had a different sonar system with outer beams that do not cover the same areas as the EM100's outer beams due to the difference in swath width and beam width.

Table 4: The rms noise in the center beams

Platform	Beam	Line	Course	Depth	σ (m)
DOLPHIN	16				1.5
Littlehales	16	B03	139°	450	1.1
Whiting	9				3.9
Whiting	10				4.1
DOLPHIN	16				1.9
Littlehales	16	B04	319°	410	1.6
Whiting	9				3.2
Whiting	10				3.7
DOLPHIN	16				2.0
Littlehales	16	B07	139°	290	1.3
Whiting	9				2.8
Whiting	10				2.5
DOLPHIN	16				2.1
Littlehales	16	P1,2	051/231°	300	1.9

The noise values shown in Tables 4 and 5 were computed with the method explained in Section 4.3 after all dropouts were discarded. The sampling rate of the HC II is much slower than that of the EM100 so fewer samples are

available to compute the noise of the *Whiting*/HC II. For example, we have approximately 900 samples from the DOLPHIN/EM100 and only about 180 samples from the *Whiting*/HC II for line B03. From observation of the σ values in Table 4, we see that data from the DOLPHIN/EM100 is consistently a little noisier than that collected by the *Littlehales*, regardless of the direction of travel. It is also less noisy than the data from the *Whiting*. Notice that in all cases the standard deviation is very small, especially relative to the average depth.

Table 5: The rms noise in the outermost beams

Platform	Beam	Line	Depth	σ (m)
DOLPHIN	1	B03	430	1.0
DOLPHIN	32	B03	480	1.6
Littlehales	1	B03	400	1.0
Littlehales	32	B03	480	0.9
DOLPHIN	1	B04	440	2.6
DOLPHIN	32	B04	380	2.0
Littlehales	1	B04	440	2.1
Littlehales	32	B04	380	1.8
DOLPHIN	1	B07	290	1.5
DOLPHIN	32	B07	310	1.9
Littlehales	1	B07	280	1.3
Littlehales	32	B07	320	1.6
DOLPHIN	1	P1	310	2.4
DOLPHIN	32	P1	290	2.5
Littlehales	1	P1	310	2.1
Littlehales	32	P1	290	2.1

Opposite to what was expected and obtained for other systems [10], the noise in the outermost beams is not consistently larger than the noise in the center beams. The outer beams of the DOLPHIN are also noisier than the corresponding beams of the *Littlehales*, the same as the center beams. Although not all beams were compared, we conclude that most of the time the data collected by the ship has a lower level of noise than the data collected

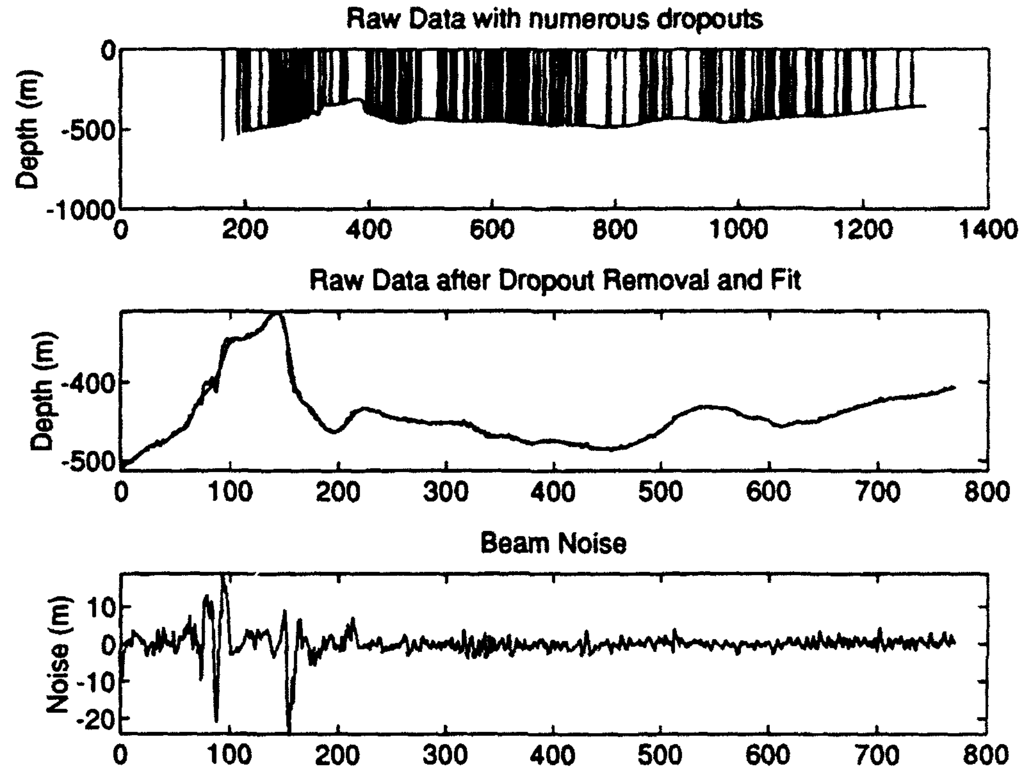

Fig. 14: Spurious noise in *Littlehales* data

by the ROV, but the difference is small (between 0.0 and 0.7 m for the data shown in Tables 4 and 5), and may be negligible since the σ itself is very small for intermediate depths. Notice also that the absolute noise (in meters) increases with increasing depth. Further noise analysis will be presented shortly for shallow flat areas, where it is meaningful to give rms error as percentage of depth.

In certain instances — e.g., when the original data has too many consecutive dropouts, or when slopes are extremely steep — the clean raw data signal has discontinuities or sudden changes in depth, which in turn cause the noise computed for those areas to be larger than the actual system noise we are trying to compute. For example see Fig. 14, where data from beam

number 1 of the EM100 in the *Littlehales* are shown. Notice that there are not only numerous dropouts all along the line reducing the amount of useful data considerably but also the difficulty in fitting a curve to the raw data around samples number 90 and 160 of the middle plot. This is reflected in the bottom plot, where large values of noise are obtained around those samples. These large values of noise do not occur very frequently, but they very much alter the resulting rms noise computation if taken as being system noise. In computing the σ values given in this report, we discard these extreme noise values and compute the rms noise from the remaining samples only since we know these extremes are due to the improper smooth fit. The rms noise values for the data shown in Fig. 14 are $\sigma = 3.3$ m when spurious noise is considered, and $\sigma = 2.1$ m otherwise.

In analyzing the noise we noticed that the noise increased as the depth increased; e.g., see Table 5 and Fig. 4 . Further analysis showed that the noise as percentage of the depth stayed relatively constant. In the top plot of Fig. 4 we show noisy center beam raw data from a section of line B03 collected by the DOLPHIN, together with the smooth fitted curve we use in computing the noise. The bottom plot of Fig. 4 shows the increasing noise with increasing depth. Splitting the data shown in five equally long pieces, we obtain the results shown in Table 6. Notice that at intermediate depths the noise is such a small percentage of the depth that it is negligible for all practical purposes.

Table 6: Depth dependent rms noise

Avg. depth	σ	% Depth
371	0.68	0.2
391	0.63	0.2
414	0.77	0.2
425	0.91	0.2
443	1.13	0.3

To meet accuracy standards of the IHO, the total error in measuring depths must, with a probability of at least 90%, not exceed 1% of the depth, and rms errors with a normal distribution should not exceed 0.6% of the

depth. The data shown in this table would clearly meet the required IHO standard for rms errors, if this residual noise were the only error present.

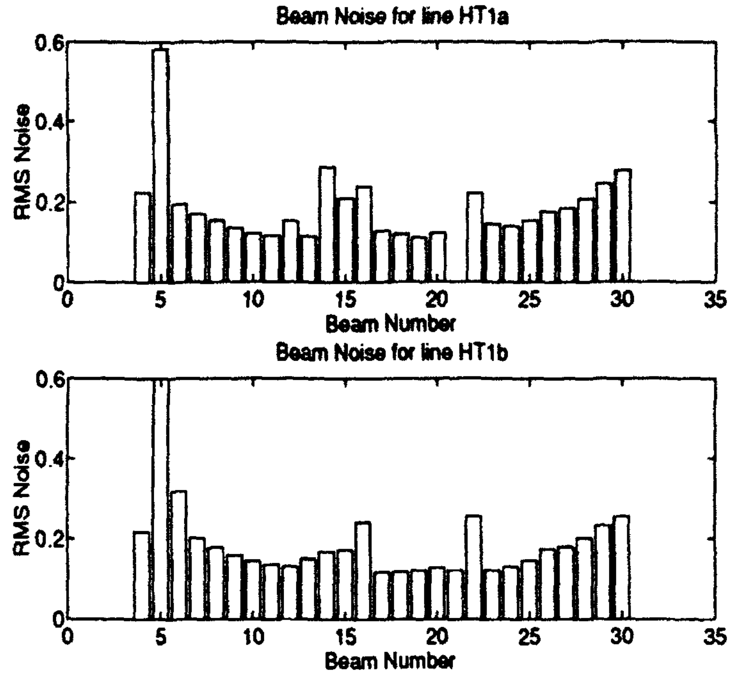

Fig. 15: Beam noise for DOLPHIN/EM100

We also studied the noise in each of the 32 beams of the DOLPHIN/EM100 system over a flat area; the heave test area was selected for this purpose. Unfortunately, the area was so shallow — around 40 m — that the ultrawide mode was used and we therefore don't have data for the outermost beams. The results for the beams that had depth registered are shown graphically in Fig. 15, where the same line was run in opposite directions. The recorded depths for beam number 5 which shows a much higher rms noise level than all other beams are shown in the bottom plot of Fig. 16. The top plot is a more typical and well behaved beam, beam number 10, although any other could have been chosen. We see that beam five has many spurious depths that go down to about 43 m, while most samples stay at about 38 m. The causes of these "semidropouts" are unknown, and they must be considered

when computing noise or errors. We also expected the center beams to be less noisy than the port or starboard beams. We don't know why the center appears noisier in this area, but further analysis showed that this is not usually the case, which agrees with results from other systems [10].

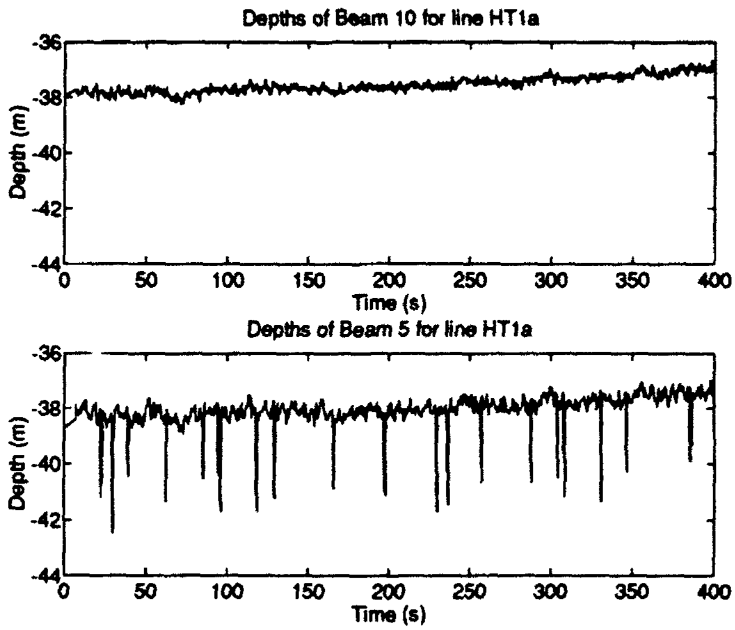

Fig. 16: Spurious noise in beam 5 of DOLPHIN data

Figure 17 shows the depths of beams 16 and 10 of the DOLPHIN/EM100 for line HT1b, where we see the unexpected behavior of the center beam, beam 16, being considerably noisier than an intermediate beam, beam 10.

We analyzed the frequency response of the noise on center beam 16 of the DOLPHIN/EM100, and plotted it together with the power spectral density of the heave registered. These power spectral densities obtained for lines HT1b are shown in Fig. 18. The power spectrum estimate is performed with FFT analysis of two sequences (the heave and the noise) using the Welch method of power spectrum estimation. The sequences are divided into a number of sections and an FFT is used on successive sections that are previously Hanning windowed and then they are accumulated. As discussed previously, it seems that the noise is not due to heave, and their spectra are

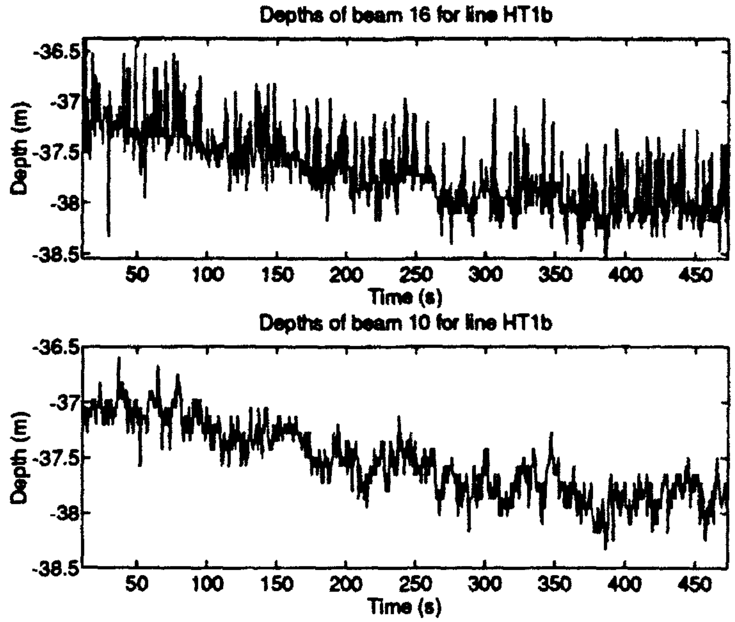

Fig. 17: Beam noise for DOLPHIN/EM100 at about 40-m depth

very different from one another. Noise is relatively constant with frequency (flat or white), while the power in the heave signal decreases rapidly with increasing frequency

The same noise analysis was done on DOLPHIN data for another flat area, a little deeper (extra data from turns after line B24). The results are shown in Fig. 19, where we show rms noise vs. beam number, and in Fig. 20, where the depth data and the noise are shown. In Fig. 20 the top plot shows the raw data for the center beam and the smooth fit to the data that was used to compute the random noise shown in the bottom plot. The depths in this area varied from 99 to 102 m, which gives a noise of around 0.1% of the depth for beams close to nadir and less than 0.25% for all beams. Notice also that the rms noise computed is not quantization error since depths are quantized to 0.075 m by the EM100, which introduces a quantization error of only about 5x10^{-4} m.

The histogram of the noise in the center beam is shown in Fig. 21, and its power spectrum in Fig. 22, where the dashed lines show the 90% confidence

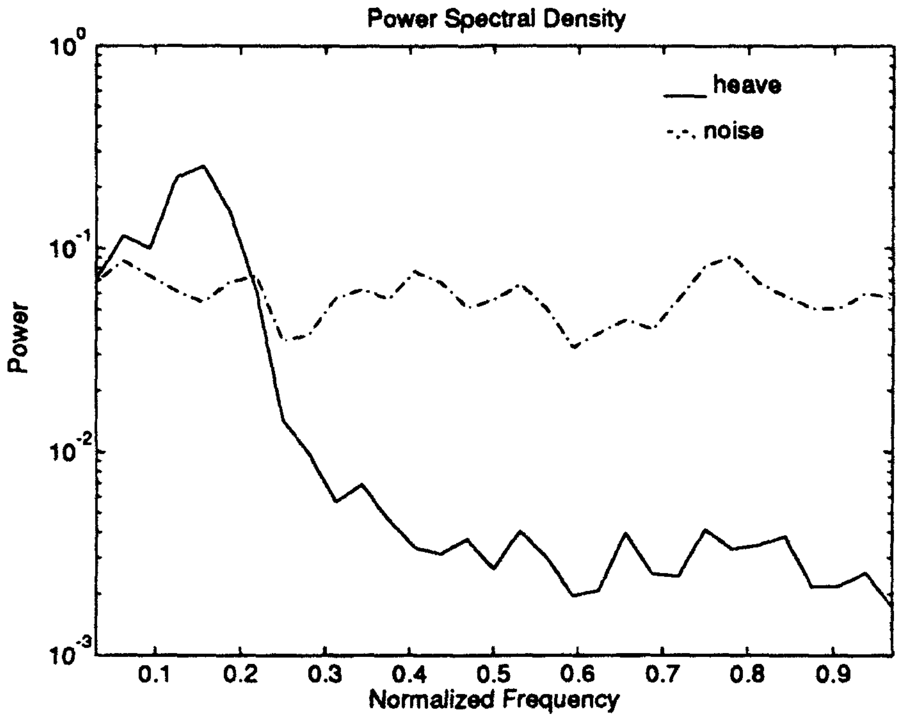

Fig. 18: PSD of noise and heave for DOLPHIN data

interval. We see that the signal assumed to be the noise in the raw data is quite flat and its distribution approaches a Gaussian pdf. The noise, therefore, can be assumed to be Additive White Gaussian Noise (AWGN), and ergodicity may be assumed if the topography is relatively smooth.

Extensive comparisons of system noise were not performed between DOLPHIN and *Whiting* mainly due to the difference in the sonars installed, but it was frequently noticed that *Whiting*'s data appeared noisier than DOLPHIN's. For example, see Fig. 23, where the depths registered at the center beams of both systems are shown.

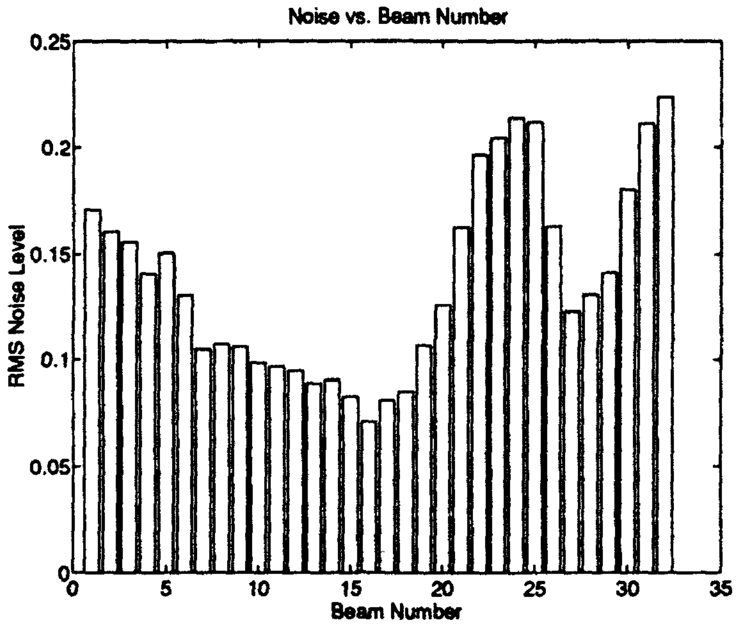

Fig. 19: Beam noise for DOLPHIN/EM100 at about 100-m depth

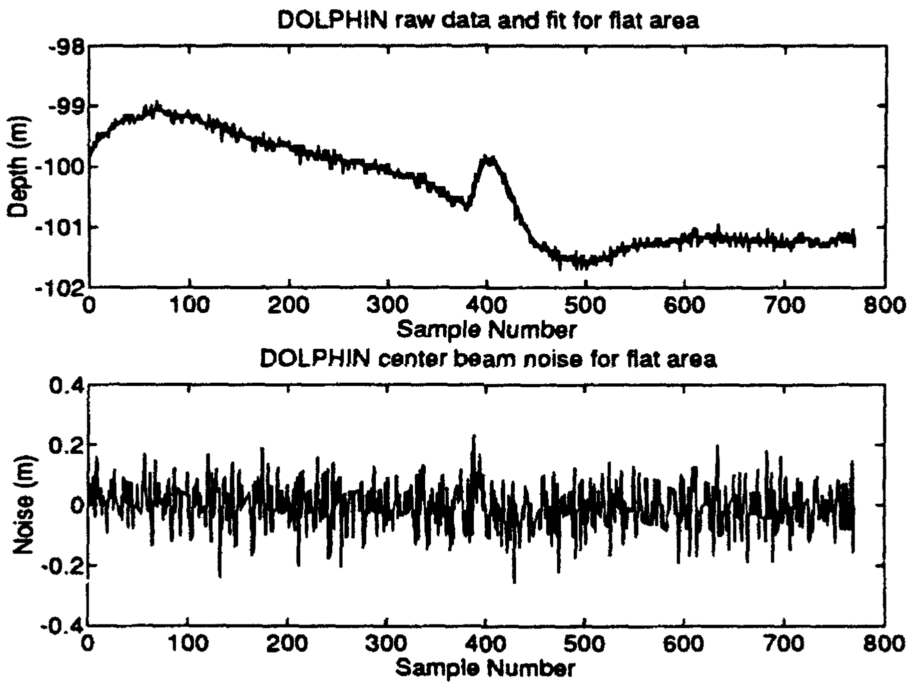

Fig. 20: Noise in DOLPHIN data for a flat area

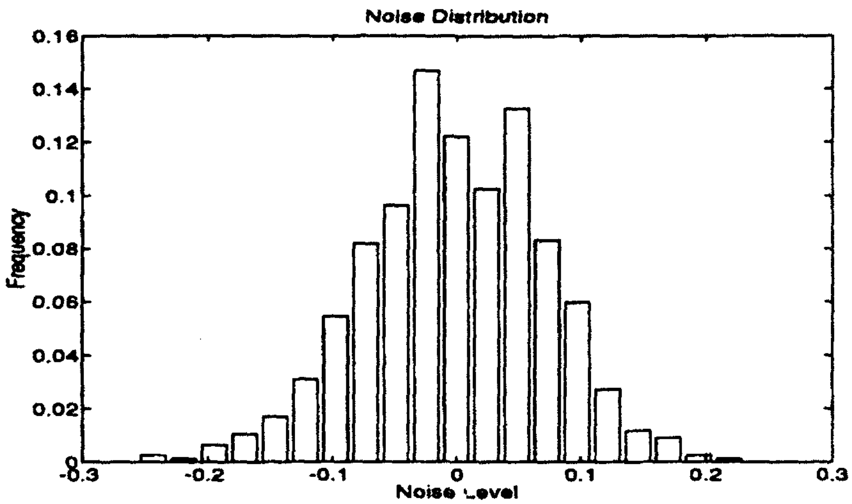

Fig. 21: Histogram of noise in DOLPHIN data for a flat area

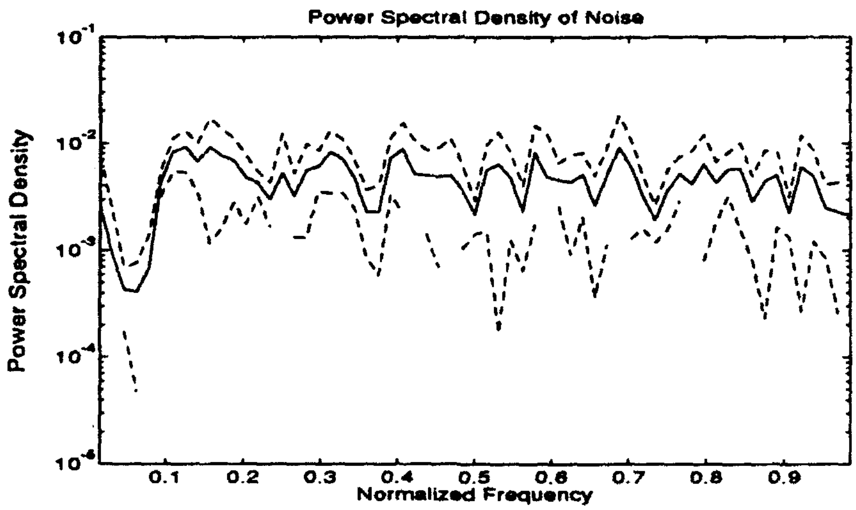

Fig. 22: PSD of noise in DOLPHIN data for a flat area

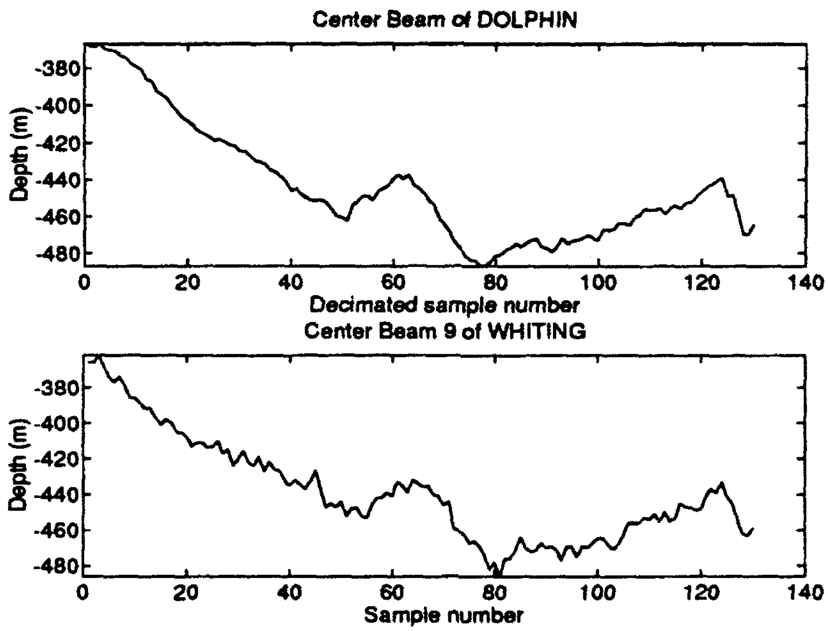

Fig. 23: Bathymetry from DOLPHIN and *Whiting*

5.4 Repeatability Test

To determine the repeatability of DOLPHIN's bathymetry generation, we compared data from line C1 that was collected on two different dates. This line produced data for a long and narrow strip. Due to the difference in dimensions in the lat/lon plane, standard gridding programs were not used to avoid excessive extrapolation. Instead, programs were written to grid a small square area at a time. Statistics were then computed for the small area. Some results are shown in Table 7 in the next section for the area between $37^\circ\ 02'\ 03.00''N, 75^\circ\ 13'\ 24.50''W$ and $37^\circ\ 02'\ 05.23''N, 75^\circ\ 13'\ 28.98''W$, with depths between 35 and 40 m. The data were collected on 5, 6, and 7 August 1992, and data from 5 August 1992 are taken as the reference.

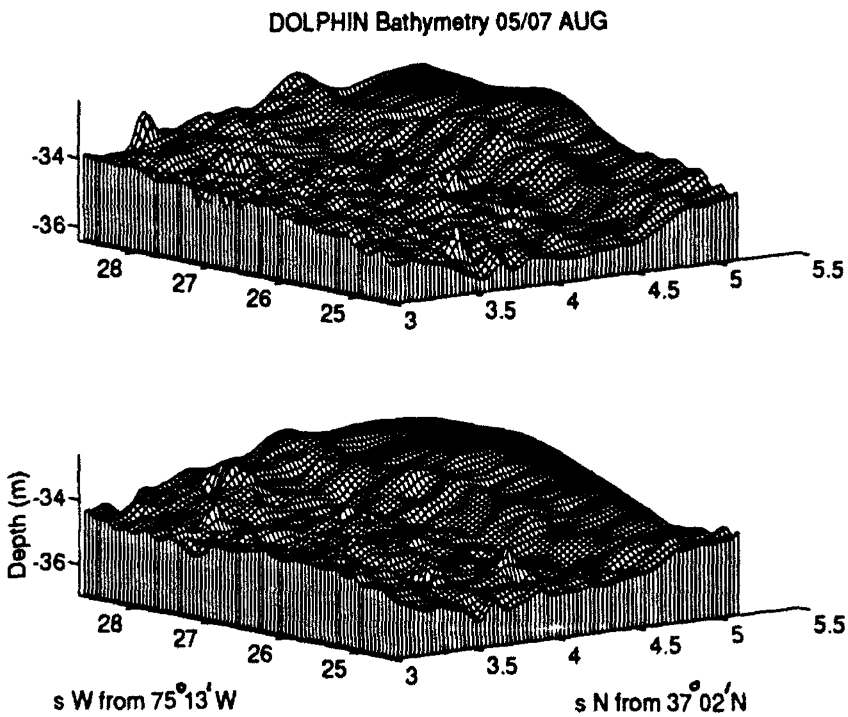

Fig. 24: DOLPHIN bathymetry for a section of line C

The bathymetry produced from two of these data sets, namely, 5 and 7 August 1992, are shown as surface plots in Fig. 24 top and bottom, respec-

tively. They visually agree well, having very close depths and very similar morphology. Statistics for the difference for these and other sets of data are given in Table 7 in the next section of this report. There we see that the soundings have an rms difference of between 1 and 1.5% of the depth.

Figure 25 shows the distribution of the differences in bathymetry computed between DOLPHIN data of parts of line C1 from 5 August 1992 and 6 August 1992 (top plot), and between 5 August 1992 and 7 August 1992 (bottom plot). Both plots indicate a normal distribution of the difference in depth, with mean close to zero. The distribution of the difference between 5 August 1992 and 7 August 1992 is narrower and taller, corroborating that the results obtained for these two days are closer to one another than for 5 August 1992 and 6 August 1992, as shown by the rms differences in Table 7.

5.5 Comparison of Bathymetry

The area for the bathymetry comparison shown in Figs. 26–29 is from 37°04′15″N to 37°04′30″N and from 74°38′30″W to 74°39′00″W. These figures show the gridded bathymetry in the form of surface plots, for each of the three platforms, as well as the depth difference surfaces. The same gridding algorithm was used on the three sets of data. Looking at the surface plots it is obvious certain differences exist between the bathymetry generated by the various systems, as expected. Also clear, though, is the fact that the topology generated by the three is quite similar, with depths that generally closely agree.

The corresponding 50-m contours are shown in Fig. 30. The contours generated did not lay on top of one another; even contours generated from the same system cannot be expected to agree completely [11]. In some cases the contour line produced by DOLPHIN is found between those of *Whiting* and *Littlehales*. Clear in Figs. 26–28 and 30 is that the bathymetry produced from data collected by DOLPHIN is smoother than that of either ship.

The feature at about $37^0 04' 17'' N, 74^0 38' 44'' W$ in Fig. 30 seems to be a gridding artifact, and it was not produced by gridding DOLPHIN's data. The spike produced at the top right corner of *Littlehales*'s bathymetry is also a gridding artifact. These are usually smoothed by hand after postprocessing [8]. Fig. 29 shows the difference surface produced by comparing DOLPHIN's bathymetry to *Littlehales*'s (top) and to *Whiting* (bottom).

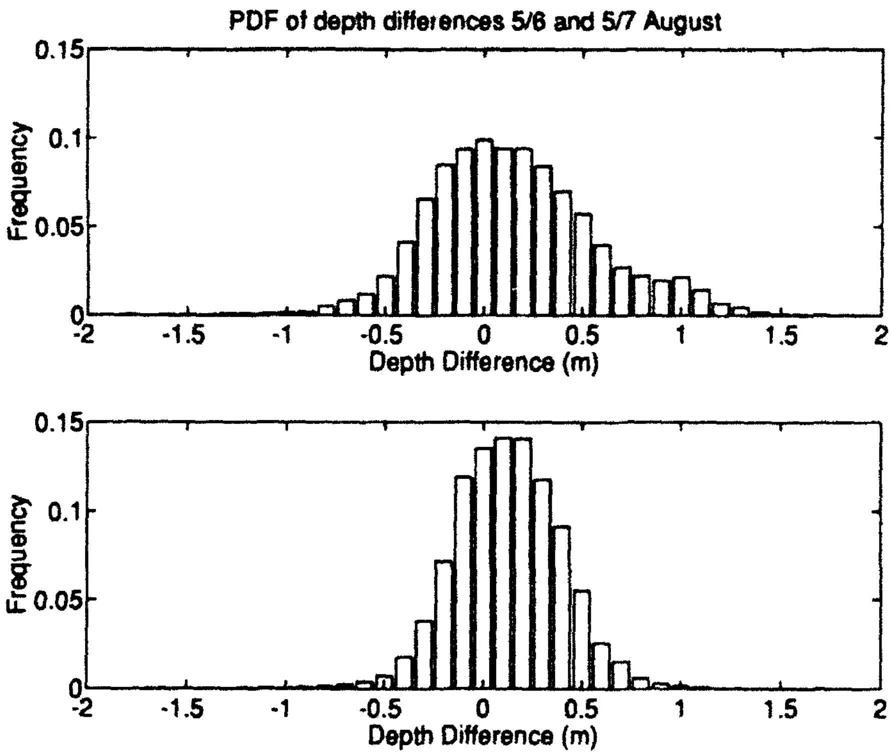

Fig. 25: Histogram of depth differences

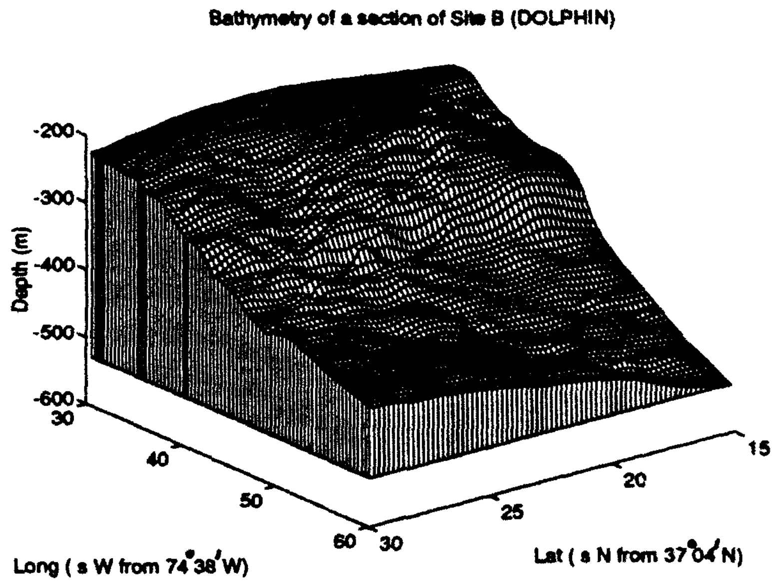

Fig. 26: Bathymetry from DOLPHIN

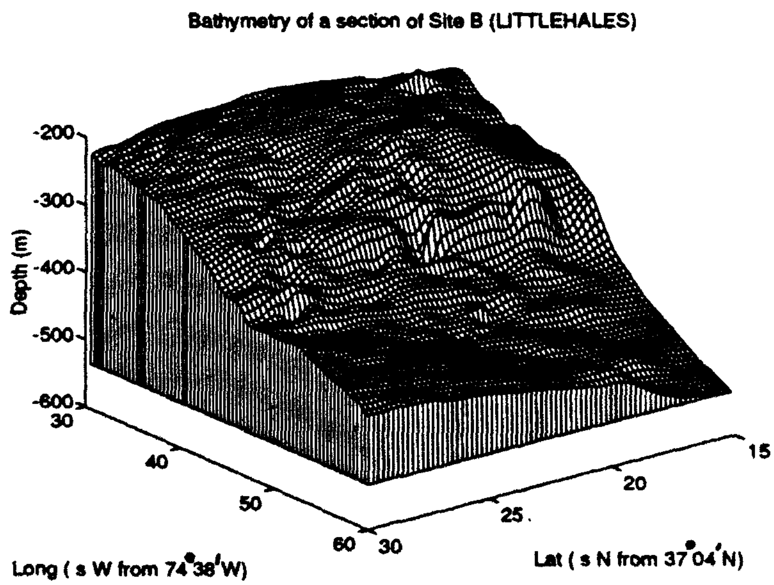

Fig. 27: Bathymetry from *Littlehales*

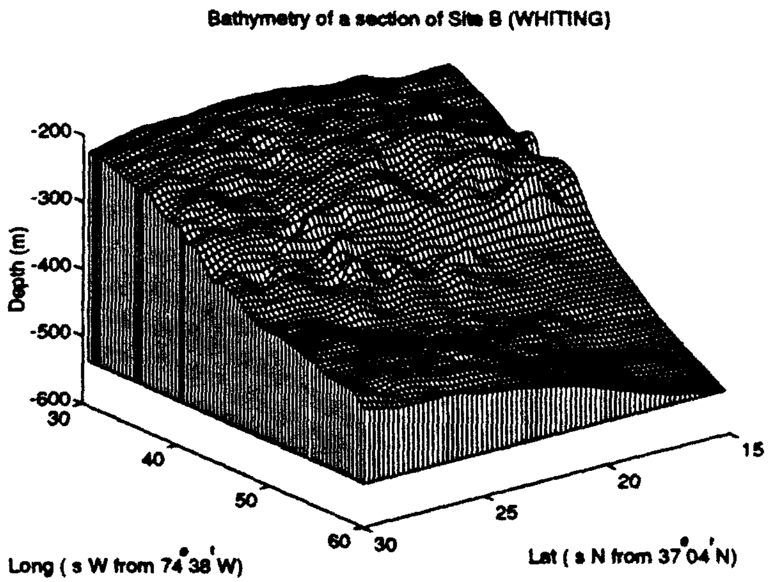

Fig. 28: Bathymetry from *Whiting*

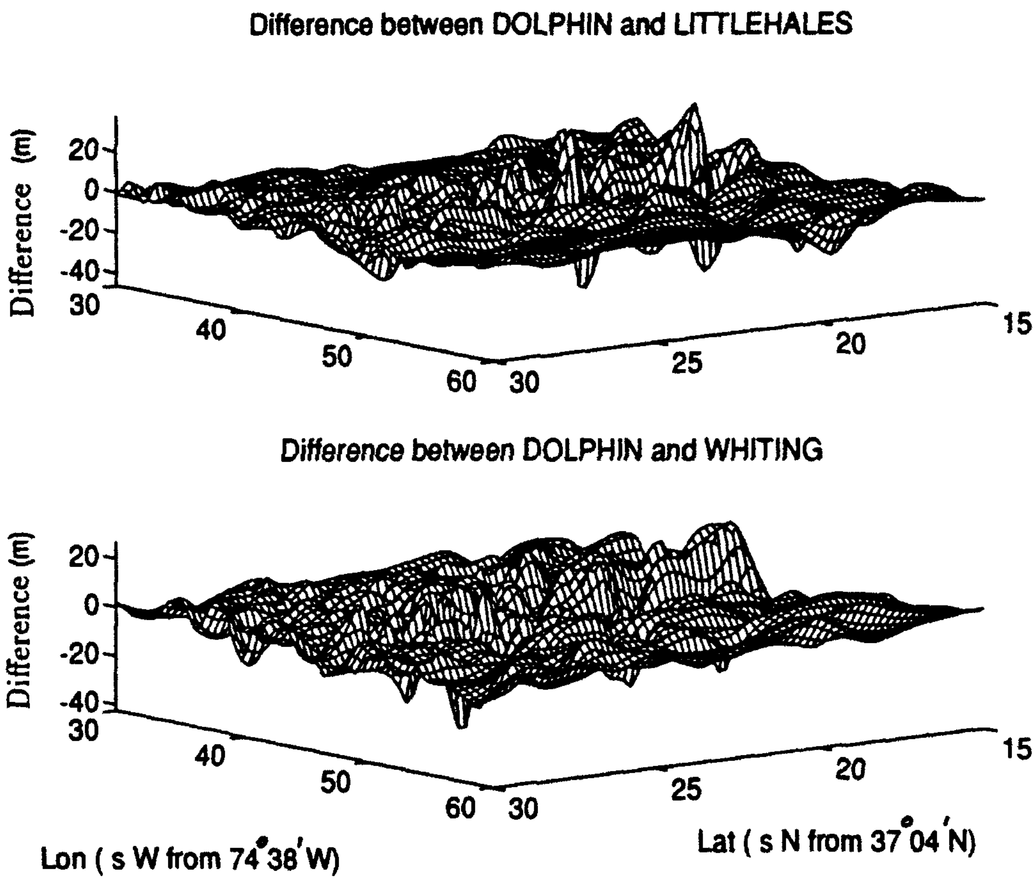

Fig. 29: Difference in bathymetry

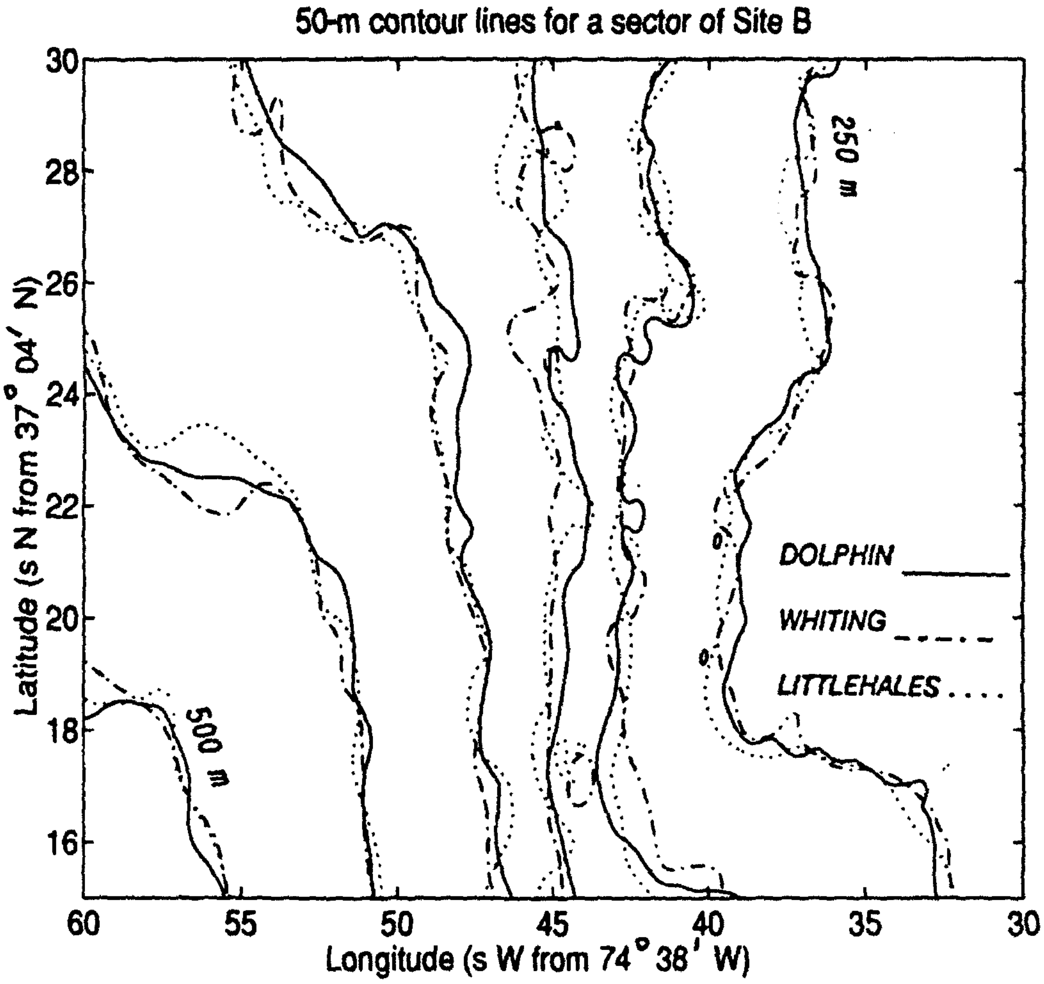

Fig. 30: Depth contours

Table 7 shows the statistics of the difference between the bathymetry generated by DOLPHIN/EM-100, *Whiting*/HC II, and *Littlehales*/EM100; it also shows comparison data for DOLPHIN/EM-100 on three different dates, as discussed in the previous section. The gridded points used for computation of statistics were obtained by interpolation within the two-dimensional function described by the nonuniformly spaced vectors (Lat,Lon,Depth) using an inverse distance method.

Table 7: Bathymetry comparison

	In Meters			Percentage of depth			
System	μ	σ	rms	μ	σ	rms	pdf
DOLPHIN vs. *Littleh.*	-1.73	6.33	6.56	0.58	1.90	1.99	normal
DOLPHIN vs. *Whiting*	-1.25	6.21	6.35	0.28	1.88	1.90	normal
Littleh vs. *Whiting*	0.48	6.97	6.99	-0.32	2.23	2.25	normal
DOLPHIN C1(05/06)	0.15	0.45	0.48	-0.45	1.33	1.41	normal
DOLPHIN C1(05/07)	0.12	0.29	0.31	-0.35	0.83	0.91	normal
DOLPHIN C1(06/07)	-0.03	0.42	0.42	0.08	1.21	1.22	normal

In Table 7 μ is the mean difference between the pair of systems compared, σ is the standard deviation, and rms is the root mean square value, as given in (2), (3), and (4), respectively. The rms and σ differ very little due to the small value of the difference μ. On the average, the gridded depths from DOLPHIN differ from those of *Whiting* by less than from those of *Littlehales*, which could be partly attributed to the different survey dates. Nonetheless, for this particular area, the bathymetry produced by *Whiting* is closer in the mean to that of *Littlehales* than to that of the ROV. The DOLPHIN sounded shallower than the others (negative μ means the second system listed in the first column sounds deeper) in this area. More meaningful than mean difference are the columns σ and rms. Clearly the largest variation was between the bathymetry of the *Littlehales* and the *Whiting*, with the difference between DOLPHIN and its mother ship being the smallest.

If any one of the three sets of depths is taken as the "true" depth, neither of the other two systems meets IHO standards since the rms errors do exceed

0.6% of the depth; they are all close to 2%. There seems to be a consensus [11] that is shared by the authors, that to expect accuracies better than 0.6% is fictitious. There are too many factors that introduce errors in the final bathymetry, a few are lack of exact velocity profiles, which produces uncertainty in ray bending computation, and difficulty in correcting for the vessel's movements [12]. Regardless of the "acceptable" percentage error, it would seem that bathymetry produced by data collected by the DOLPHIN is better than that of the ships. By this we mean that if the bathymetry from either of the other two platforms is taken as the "truth," the DOLPHIN is closer to it (as indicated by the rms error) than the other ship is. More comparisons are necessary to arrive at a definite conclusion.

6.0 Conclusions

We have presented an evaluation of the performance of the DOLPHIN ROV as a platform for collection of multibeam sonar data. Results were presented about the stability of the platform, the noise of the system, and the quality of the raw data and also of the resulting bathymetry. Comparisons were made to results obtained from data collected during the same survey by the DOLPHIN's mother ship, the *Whiting*, and from data collected at a later date by the *Littlehales.*

Our results indicate that the DOLPHIN does not consistently pitch less than the ship, and that the movement is highly dependent on the direction of travel. Also, data from the ships show spurts of high amplitude pitch that are not present in the ROV's data. The DOLPHIN pitched at a lower frequency than its mother ship, and in a more random-like fashion. We didn't find any evidence of heave being responsible for the system's noise, i.e., there was no strong correlation between the two.

All the data analyzed indicated that the *Littlehales*/EM100 system suffered from a very large number of dropouts, so that the percentage of invalid data is much larger for the ship than for the DOLPHIN/EM100. The sampling rates for these two systems were not identical so the ADR was used to compare the dropouts relative to sampling frequency. DOLPHIN had a smaller ADR. Both systems usually have more dropouts in the outer beams.

Noise analysis showed that the *Littlehales*/EM100 system has a lower noise level than the DOLPHIN/EM100, but in both cases the noise is negligible. *Whiting*'s data are noisier, but it also had a different sonar system.

The absolute noise level increases with increasing depth, but remains relatively constant as percentage of depth. Both EM100 systems suffered from spurious unexplained beam noise and did not consistently obey the trend of decreasing noise for beams approaching nadir, although this was most frequently the case. The power spectrum of the noise is flat, and the distribution of the noise is Gaussian.

Results from the repeatability test indicate that the DOLPHIN/EM100 platform collects consistent data; i.e., bathymetry produced by data sets collected in different condition closely agree. Results generated from data collected by the different platforms do not agree as closely, with rms difference of about 2% of the depth. The bathymetry between the DOLPHIN and *Whiting* differs less than than between any other pair of platforms.

The authors conclude that the DOLPHIN ROV is an excellent platform for collecting multibeam bathymetric data, and possibly other kinds of sonar data as well. The platform is stable, it introduces negligible noise to the system, suffers from very few dropouts, and produces bathymetry of quality comparable to that produced by data collected by a ship.

7.0 Suggestions for Further Work

The standard processing applied to HC II data merges navigation and raw bathymetry onto a "merged" file; this file does not contain information on roll and heave, and records depths quantized to 1 m. To the best of the authors' knowledge the only other data that the premerged raw data files contain and that can be used directly is heave. Further analysis of platform attitude movements must compare roll and heave between DOLPHIN and *Whiting*. Unfortunately the actual roll of the *Whiting* is not directly available[4]. Only after these comparisons are made can a definite conclusion be made about the relative stability of the platforms.

Data from several patch tests performed by the DOLPHIN are available and can be analyzed using the techniques presented in [13, 14] to determine pitch, gyro, time delay, and roll biases. Also available are data from overlapping beams that can be used to evaluate the errors of the outer beams, as compared to the inner beams. This analysis will complement the beam noise analysis presented in this report.

[4]Only roll at receive beam number 5 is recorded on the .HC2 files.

Many more comparisons can be made between bathymetry generated by the three systems. This is not straightforward, though, since interpolation (gridding) without extrapolations needs to be done on the data, trying to keep other factors constant, such as the number of original points per grid point. Contoured data might be a simpler way to compare bathymetry. The problem still remains of not having a "true depth" to base the comparison upon. Revision of IHO standards might need to be performed. It seems very hard to achieve rms errors not larger than 0.6% of the depth, with a 90% confidence that the total error won't exceed 1% of the depth.

Line B05 was surveyed twice, the second time with a rougher sea state. The intent was to analyze the effect of sea state on the collected data, the results are not included in this report. Also, the line was unfortunately surveyed in opposite directions.

It would be interesting to evaluate the performance of the DOLPHIN as a collection of sonar data to produce imagery. Some discussion of a possible configuration with an EM1000 is given in [4].

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